Single and Double ITCZ in Aqua-planet Models with Globally Uniform Sea Surface Temperature and Solar Insolation: An Interpretation

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Abstract

It has been known for more than a decade that an aqua-planet model with globally uniform sea surface temperature and solar insolation angle can generate ITCZ (intertropical convergence zone). Previous studies have shown that the ITCZ under such model settings can be changed between a single ITCZ over the equator and a double ITCZ straddling the equator through one of several measures. These measures include switching to a different cumulus parameterization scheme, changes within the cumulus parameterization scheme, and changes in other aspects of the model design such as horizontal resolution. In this paper an interpretation for these findings is offered.

The latitudinal location of the ITCZ is the latitude where the balance of two types of attraction on the ITCZ, both due to earth's rotation, exists. The first type is equator-ward and is directly related to the earth's rotation and thus not sensitive to model design changes. The second type is poleward and is related to the convective circulation and thus is sensitive to model design changes. Due to the shape of the attractors, the balance of the two types of attractions is reached either at the equator or more than 10 degrees away from the equator. The former case results in a single ITCZ over the equator and the latter case a double ITCZ straddling the equator.

1. Introduction

It has been known for more than a decade that earth's rotation alone, without the presence of equator-to-pole gradient in radiative-convective equilibrium temperature, is sufficient to give rise to the ITCZ (intertropical convergence zone) and atmospheric general circulation. Although this general circulation is quite different from the observed general circulation (for example, the Hadley circulation is much weaker than what is observed), it is a useful tool to gain insight into some basic mechanisms governing the atmospheric general circulation. Aqua-planet models with globally uniform sea surface temperature (SST) and solar angle, which have no equator-to-pole gradient in radiative-convective equilibrium temperature, have been used by many researchers. Sumi (1992) studied the effects of evaporation rate and the earth's rate of rotation on the organization of convective activities. In Sumi's study the Kuo (1965) parameterization was used. He found, among other things, that by merely doubling the horizontal resolution a single ITCZ at the equator turned into a double ITCZ straddling the equator. Sumi interpreted this result as a consequence of the low-resolution model's not having sufficient resolution to resolve the double ITCZ and thus resulting in a single ITCZ. We will offer a different interpretation. Sumi also found that by switching to Manabe's (1965) moist convective adjustment scheme (MCA), the double ITCZ remains. (Note: Sumi did not use constant solar angle but used globally uniform net radiative cooling rate. This did not change things qualitatively.) Kirtman and Schneider (2000) also did a similar kind of experiment but with the relaxed Arakawa-Schubert scheme (hereafter, RAS (Moorthi and Suarez 1990)) and obtained a single ITCZ over the equator, whereas our similar experiments with the same scheme gave double ITCZ (Chao 2000). We also found that switching to MCA can turn a double ITCZ into a single ITCZ over the equator (Chao

2000). Furthermore, we have found that by imposing on RAS a condition of boundary layer relative humidity being greater than a critical value before convection is allowed to occur and through increasing this critical value, RAS can be made to behave like MCA in the sense that a double ITCZ can be switched to a single ITCZ over the equator (Chao and Chen 2001).

In summary, previous studies have shown that, by means of one of several model design changes, the structure of the ITCZ in an aqua-planet model with globally uniform SST and solar insolation can change between a single ITCZ at the equator and a double ITCZ straddling the equator. These model design changes include switching to a different cumulus parameterization scheme, changes within the cumulus parameterizaton scheme, and changes in other aspects of the model, such as horizontal resolution. Sometimes only one component of the double ITCZ shows up; but still this is an ITCZ away from the equator, quite distinct from a single ITCZ over the equator. Chao and Chen (2001) have made an initial attempt to interpret these findings based on the concept of rotational ITCZ attractors that they introduced. The purpose of this paper is to offer a more complete interpretation.

2. Interpretation

According to the linear theory, convection occurs when the squared frequency of the inertial gravity wave (in an rotating atmosphere with hydrostatic approximation):

$$\sigma^2 = f^2 + \alpha^2 (\partial \ln \theta / \partial z) + |F|, \qquad (1)$$

which is from Eq. (8.4.23) of Gill (1982), turns negative. In Eq. (1), f is the Coriolis parameter, α is the ratio of horizontal to vertical wave numbers, θ is the potential temperature for dry atmosphere and is the equivalent potential temperature when the atmosphere is saturated. For unsaturated atmosphere, it suffices to say that θ denotes a similar quantity. $\partial\theta/\partial z$ is the vertical stability. We have added a positive $|F|$ term in Eq. (1) to represent the effect of friction. Our knowledge about Eq. (1) is not complete, since the exact definition of θ is not given and how θ is related to the circulation field is not completely clear. However, we do not have to use Eq. (1) in an exact way. For our purpose we only intend to point out that convection occurs when a not-yet-well-defined vertical instability is large enough to overcome the stabilizing effects of rotation (i.e., the f^2 term) and friction. The fact that f^2 is a positive term and thus can cancel partially the negative second term on the right hand side of Eq. (1) means that the earth's rotation has a stabilizing effect. The dynamic reason for the stabilizing effect of rotation was explained in Chao and Chen (2001). Thus, according to the f^2 term in Eq (1) the equator is the most favored location for convection. In other words, the equator is an attractor for convection (or more precisely, the upward branch of the convective cells favors the equator), or the ITCZ. Additionally, there is a second effect of earth's rotation embedded in the second term on the right hand side of Eq. (1). The vertical instability is maintained by the high θ in the boundary layer as a result of the boundary layer inflow toward the precipitation centers. (Instantaneously the ITCZ consists of many convective centers along a zonal belt.) With a higher f, the inflow takes on a more spiraling path with higher speed, thus picking up more moisture. Thus the second effect of earth's rotation favors high latitudes. As a result, there are two additional attractors for convection at the poles.

The two types of attraction due to earth's rotation are depicted schematically in Fig. 1. Curve A is the attraction due to the first effect with positive value denoting southward attraction; its value is zero at the equator, the center of the attractor. And curve B (the dashed curve) is the attraction due to the second effect of earth's rotation or due to the second term on the right hand side of Eq. (1) with positive value denoting northward attraction. Being related to the thermodynamics and the circulation of the model atmosphere, curve B depends on the choice of the cumulus parameterization scheme (whereas curve A does not). Like the f^2 term, the $|F|$ term is positive and has a stabilizing effect. We have incorporated the effect of the $|F|$ term in curve B to give curve B a somewhat smaller magnitude. Both curves are anti-symmetric with respect to the equator; thus only the picture in the northern hemisphere is given. Curve A is obtained by assuming that its magnitude is related to the latitudinal gradient of f^2; i.e., $\partial f^2 / \partial \phi = 8\, \Omega \sin\phi \cos\phi$ (where Ω is earth's rate of rotation and ϕ the latitude). It is reasonable to assume that the magnitude of curve A is large when the latitudinal gradient of f^2 is large. Another supporting argument for using the latitudinal gradient is that we can identify the location of the ITCZ as where σ^2 is a minimum, or $\partial\sigma^2 / \partial\phi = 0$, at least based on the linear theory. Thus at the location of the ITCZ $\partial f^2/\partial\phi$ is balanced by the latitudinal gradient of the second term on the right hand side of Eq. (1) (assuming $|F|$ is absorbed in this term.), or curve A is balanced by curve B. Since we have plotted curve A only in a schematic way, we only need to assert that curve A is zero at the equator and increases first and then decreases northward and reaches zero at the north pole. This assertion is reasonable in the sense that the "force" of attraction is supposed to be zero at the center of the attractor (the equator) and curve A is supposed to be zero at the north pole (an unstable equilibrium location) also due to the symmetry there. Also we need to assert that the slope of curve A at the equator is nonzero according to the above equation for $\partial f^2/\partial\phi$.

As we mentioned above, curve B (positive means northward attraction) is related to the dependence of the second term on the right hand side of Eq. (1) on the earth's rotation and is due to two attractors at the poles. In the northern hemisphere this attraction is toward the north pole, thus curve B is positive in the northern hemisphere and is zero at the north pole, the center of the attractor, and at the equator due to symmetry. In Fig. 1 we have drawn curve B in a way that can best fit the experimental results. Why the peak of curve B is in the tropical region instead of middle or high latitude remains to be explained and we will give a speculative explanation in the next section.

In Fig. 1 we have plotted curve B for both RAS and MCA. Bras is larger than Bmca, because MCA has a more stringent criterion for convection to occur (i.e, the relative humidity has to be saturated). Thus with MCA when convection does occur it is more intense and concentrated in a smaller area. Such concentration reduces the chance for convective circulation to pick up moisture at the surface. Since the slope of curve A is different from that of curve B (which is nonzero), the equator can be a stable or an unstable equilibrium. For MCA the equator is the only stable equilibrium. For RAS the equator can be a stable equilibrium, if the slope of curve A is larger than that of curve B at the equator. A stable ITCZ at the equator was obtained in an experiment using RAS with an earlier version of the model (Chao and Deng 1998, their Fig. 3; the fact that their model had an SST peak at the equator might have helped the equatorial ITCZ to exist) in addition to the two ITCZ's straddling the equator. Our experiments with RAS with the current version of the model have not yielded three concurrent ITCZ's. Somehow with RAS the slope of curve A at the equator is smaller than that of curve B. The reason for this is not clear. It is possible that the equilibrium at the equator is a weak one and can easily be overwhelmed by one of the double ITCZ in the same process that allows one of the double ITCZ to suppress the other.

Fig. 1 is supported by two experiments. Fig. 2 (from Chao and Chen 2001) shows the zonally averaged precipitation of an experiment using RAS where an above 90% boundary layer relative humidity criterion is imposed for any cumulus convection to occur in the first 200 days and the criterion is changed linearly in time to 95% in the next 100 days and remains at 95% thereafter (thus making RAS behaving more like MCA). The model used is an aqua-planet version of the Goddard Earth Observing System atmospheric general circulation model with 4^o (lat.) x 5^o (lon.) grid size and 20 vertical levels (See Chao and Chen (2001) for a brief description). The SST is a globally constant 29^o C and the solar angle is also uniform with a value of the global mean. The convection region moved from an off-equatorial position to the equator in 30 days starting day 225. This corresponds to a diminishing of curve B to below curve A and the disappearance of the intersecting point P.

Fig. 3 shows the same experiment except that the numbers of 90% and 95% are switched. The jump of the convection region away from the equatorial position around day 252 is rather abrupt. This corresponds to the fact that when the slope of curve B at the equator surpasses that of curve A, the peak of curve B already exceeds curve A by a large amount. This large difference means that the force pulling the ITCZ away from the equator is very large and thus resulting in the abrupt jump of the ITCZ. In Fig. 1 curve Bmca represents the situation when MCA replaces RAS. It also represents the situation when the 95% criterion is applied to RAS. The difference between curves A and B in Fig. 1 gives the net attraction due to earth's rotation. Thus in the case of RAS the net force (positive is southward) is zero at the equator and decreases with latitude first and then increases back to zero at around 13^oN. In the case of MCA, it is zero at the equator and increases with latitude and then drops to almost zero at 13°N and then increases again after that. These are the results found experimentally in Chao (2000, his Fig. 8.)

3. Discussions

As stated above the peak of curve B is close to the equator. The exact reason is yet to be ascertained. Here, we will offer a speculative explanation. A convective system in the northern hemisphere, according to the definition of curve B, experiences attraction toward the north pole and this attraction is related to the gradient of f; thus it increases toward the equator. But when close to the equator, due to the large size of the convective system, part of the convective system covers a domain south of the equator and thus experiencing the attraction from the attractor at the south pole. At the equator the attraction due to both poles cancel and curve B should be zero. Therefore curve B has a peak close to the equator.

Sumi's results showed that the single ITCZ over the equator can turn into a double ITCZ when the model horizontal resolution is doubled. His interpretation was that the low-resolution model was not enough to resolve the double ITCZ. However, we would put forth a more subtle interpretation. Cumulus convection scheme becomes more active when the grid size is reduced, due to the fact that larger convergence is more likely to occur as the grid size is reduced. Thus, when the horizontal resolution is doubled, the cumulus convection scheme is effectively changed and becomes more vigorous. Equivalently, the absolute value of the negative stability associated with convection in Eq. (1) becomes larger. This corresponds to a rising of curve B in Fig. 1. When curve B is raised, or when the slope of curve B at the equator is increased and surpasses that of curve A, the intercept between curves A and B moves away from the equator. Thus a single ITCZ at the equator switches to a double ITCZ straddling the equator.

In an experiment in which the SST remains uniform but increase from 29° C to 32° C in 400 days the latitudinal location of the ITCZ did not change systematically aside from some short term (~2 weeks) fluctuations.

Surface friction has a damping effect. In Eq. (1) the effect of surface friction is represented as a part of the positive term $|F|$ on the right hand side (the other part is the internal friction). Thus we can consider curve B in Fig. 1 as representing both the attraction due to the second effect of rotation and friction. Therefore, when surface friction is removed curve B should be raised somewhat. This will result in a poleward movement of the ITCZ. An experiment where the surface frictional coefficient is multiplied by a factor of 2 which, after staying at 2 for 100 days, is reduced to zero in the next 400 days indeed shows a poleward movement of the ITCZ (figure not shown). Internal friction is expected to have similar, though much smaller, effect.

When the model is in the double ITCZ regime, sometimes one component of the double ITCZ does not appear, resulting in one ITCZ away from the equator (as in Figs. 2 and 3). The reason for this is yet to be explained.

In our discussion we have not touched upon the latitudinal dependence of α in Eq. 1. Since a spectrum of gravity waves are excited, α is not a single value; but it does have a dominant value. How this dominant value depends on the latitude is yet to be understood.

4. Summary

In summary, previous studies have found that through one of several model design changes the ITCZ structure in the aqua-planet model with constant SST and solar insolation angle can switch between a single ITCZ over the equator to a double ITCZ straddling the equator (in the latter case one of the ITCZ may be absent, leaving one ITCZ away from the equator.) These model design changes include switching to a different cumulus parameterization scheme, changes in the cumulus parameterization scheme, and changes in other aspects of the model. We have offered an interpretation for these findings based on the balance of two types of attractors both due to the earth's rotation, one at the equator which is independent of the cumulus parameterization scheme and the other at the pole which is dependent on the cumulus parameterization scheme. The balance of the two attractors determines the location of the ITCZ. The relative strength of the two attractors can be changed as the model design is changed, thus resulting in the switching between the single ITCZ and the double ITCZ.

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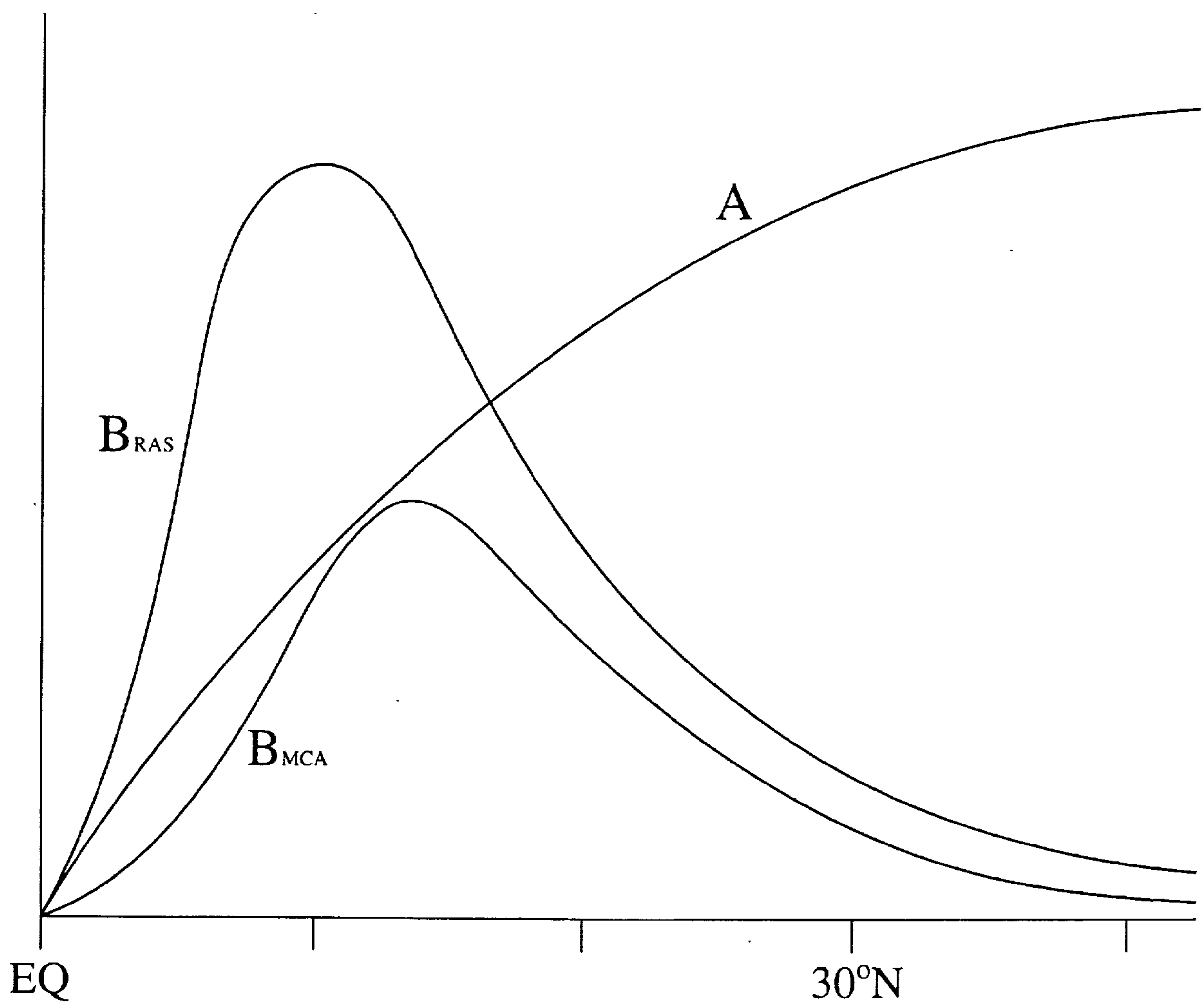
Figure Captions

Fig. 1 Schematic diagram of the two types of attraction acting on convective systems.

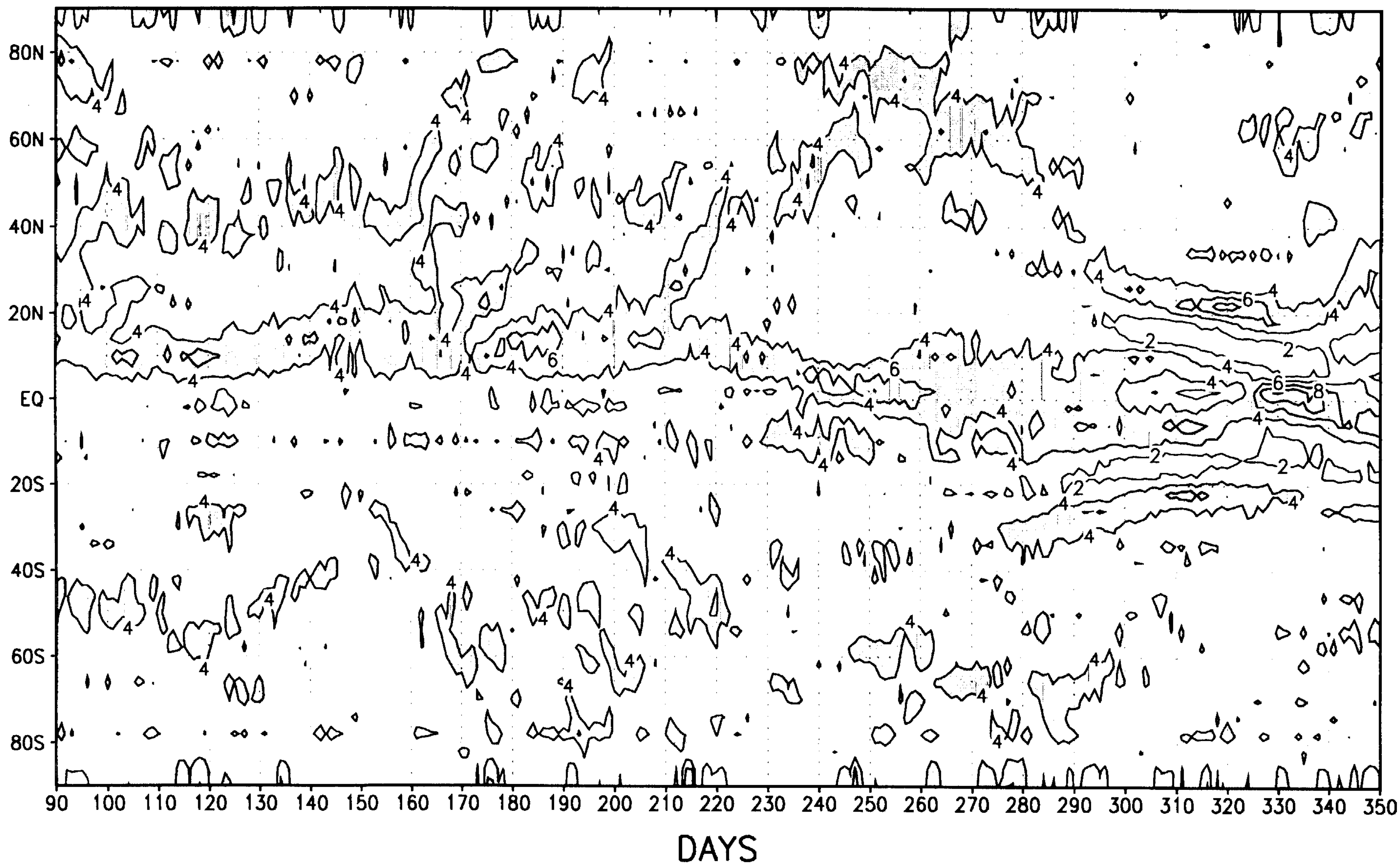
Fig. 2 Zonally averaged precipitation as a function of time in an experiment with uniform SST and solar insolation with a condition that for cumulus convection to occur the boundary layer relative humidity has to be greater than a critical value. The critical value is 90% in the first 200 days and then increased linearly in time in the next 100 day to 95%.

Fig. 3. Same as Fig. 2 except that the values of 90% and 95% are switched.

Fig 1



vc5.9a20/(R.90 -> R.95) + uniform SST



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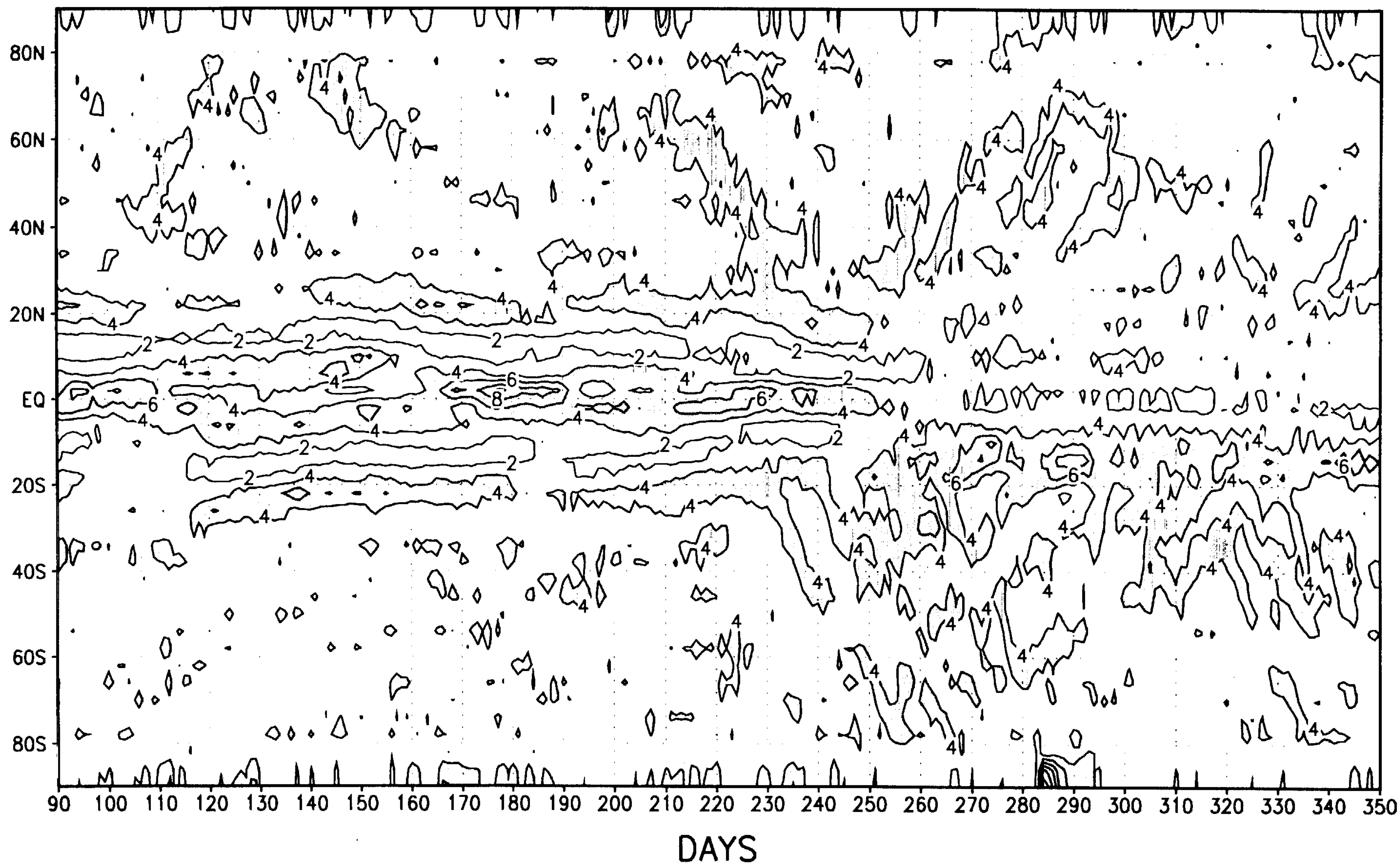

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